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Integrated Microsystems: A Revolution on Five Frontiers

When I learned we were returning to Disneyland for DARPATech 2005, I decided to get some local help with my office vision. As we dream of the future of technology, who better to talk to than Alice in Wonderland who was challenged to believe in impossible things by the White Queen in Lewis Carroll's "Through the Looking Glass."

"I daresay you haven't had much practice," said the Queen (to Alice). "When I was your age, I always did it for half-an-hour a day. Why, sometimes I've believed as many as six impossible things before breakfast."

I'm not going head-to-head with the White Queen. But to bring you along on MTO's vision for Integrated Microsystems, I am going to ask you to believe five impossible things before dinner!

Imagine the functionality of an atomic clock, a navigation grade gyroscope, a biological sensor, a CINGARS radio, and a hyperspectral imager—all smaller than your wrist watch. On top of that, imagine that this all requires less than 0.1 watt of power.

Impossible? No. In fact, this is exactly the type of capability that MTO is pursuing by driving the Integrated Microsystem Revolution on 5 frontiers: electronics, photonics, MEMS, architectures, and algorithms—our five impossible things.

MTO program managers are the engineers of the nano-world. We work on structures with dimensions smaller than a human hair to build micromachines, nanotransistors and atomic sensors. We exploit the nano world to shrink table-top platforms, like an atomic clock or a hyperspectal imager, onto platforms on a chip. Our vision of an integrated microsystem goes beyond the progression of the semiconductor-based technology of electronics, photonics, and MEMS. We are seeking a revolution at the intersections of micro-technology. We exploit new architectures and algorithms to build complete systems, or platforms, at the chipscale.

In MTO we carry the mantle of the microelectronics industry. From the discovery of the transistor over 50 years ago, to the first solid state laser, to semiconductor solar cells, to micromachined accelerometers, we enable the top of the food chain, the system engineer, to build the futuristic platforms that are the stuff of dreams.

DARPA's system offices talk about the breakthrough system concepts they are pursing, but "behind every system revolution is a component revolution." The component technologies being inserted into today's new systems were largely pioneered by MTO 5 to 10 years ago.

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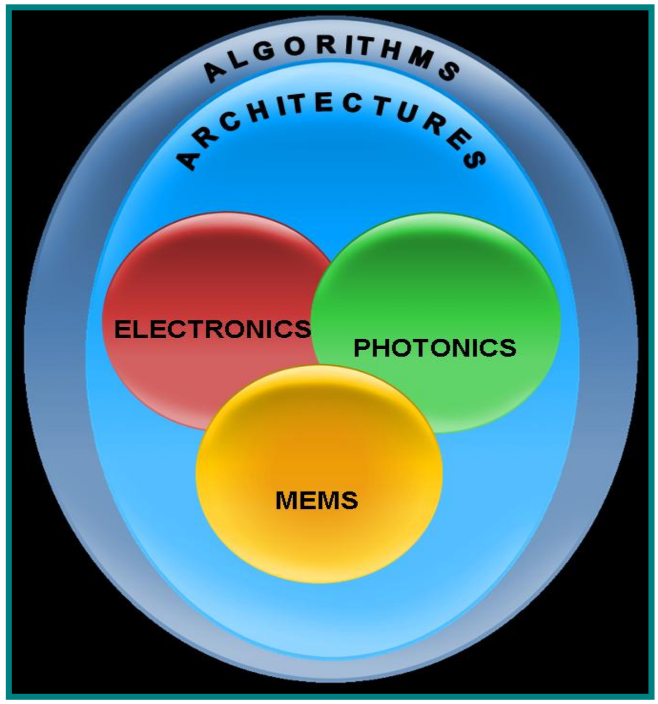
I am going to tell you about the future of component technology. The future is integrated microsystems—platforms on a chip. MTO is at the tip of the spear, pushing integrated microsystem technology into previously uncharted territory.

Historically, micro-components have been developed in three regimes: electronics, photonics, and, more recently, mechanics, or microelectromechanical systems (MEMS).

With the invention of the transistor over 50 years ago, and the integrated circuit a few years later, electronics has been the benchmark for component development. The ability to vary the resistance of a small slice of a semiconductor by applying a voltage to a control electrode—that is a transistor—has shaped all aspects of our life today.



The magic of Moore's Law, where every 2 years brings more computing power from more and better transistors, has created platforms never even dreamed of 50 years ago.

The early drive for digital circuits also gave way to the ability to generate and amplify high frequency, microwave, and millimeter wave signals with ultra-fast transistors. It was not until DARPA pioneered the production of gallium arsenide microwave monolithic integrated circuits (MMICs) to enable all solid state transmit and receive modules that active array, airborne radar became possible. Today, these radars can track multiple targets at great distances because of their distributed architecture enabled by MMIC technology. This is a clear example of a component revolution enabling a system revolution.

Another example of component technology revolutionizing platform capability is the development of uncooled night vision sensors. Night vision systems were dramatically simplified with the demonstration of micro-bolometer sensors that could discriminate long wavelength radiation without cooling. This led to practical night vision goggles for the warfighter. As a result of this micro-technology advance, the US military owned the night.

Now our adversaries have caught up and MTO is leading the drive to retake the night and own the weather by enabling future imaging systems.

By exploiting uncharted regions of the electromagnetic spectrum, we are developing imagers that can see through sand storms and smoke clouds, or dynamically be reconfigured to operate in different wavelength bins.

Today's purview of the nano-engineer is the five frontiers of electronics, photonics, MEMS, architectures, and algorithms. These five domains make up the tool set of the integrated microsystems designer. It is no longer sufficient to be an expert in developing components only within one domain. The revolutionary ideas come from crossing the boundaries and truly building platforms on a chip.

Three years ago program managers Bill Tang and Clark Nguyen had an idea to fabricate a complete atomic clock at the micro-scale. They thought they could exploit advances in micro-technology to build a vertical cavity surface emitting laser, couple it with a lens and a tiny micromachined cesium vapor cell, top it with an optical detector, wrap the whole thing with microchip control electronics and low-power frequency-locking MEMS resonators, and produce a high performance atomic clock in only 1 cubic centimeter of volume that would dissipate only 30 milliwatts of power.

To put this in perspective, a conventional atomic clock with the same target time stability is over 30 times larger and consumes 10 times more power. Acting as an engineer of the nano-world, the program manager developed a program that exploited all 5 domains.

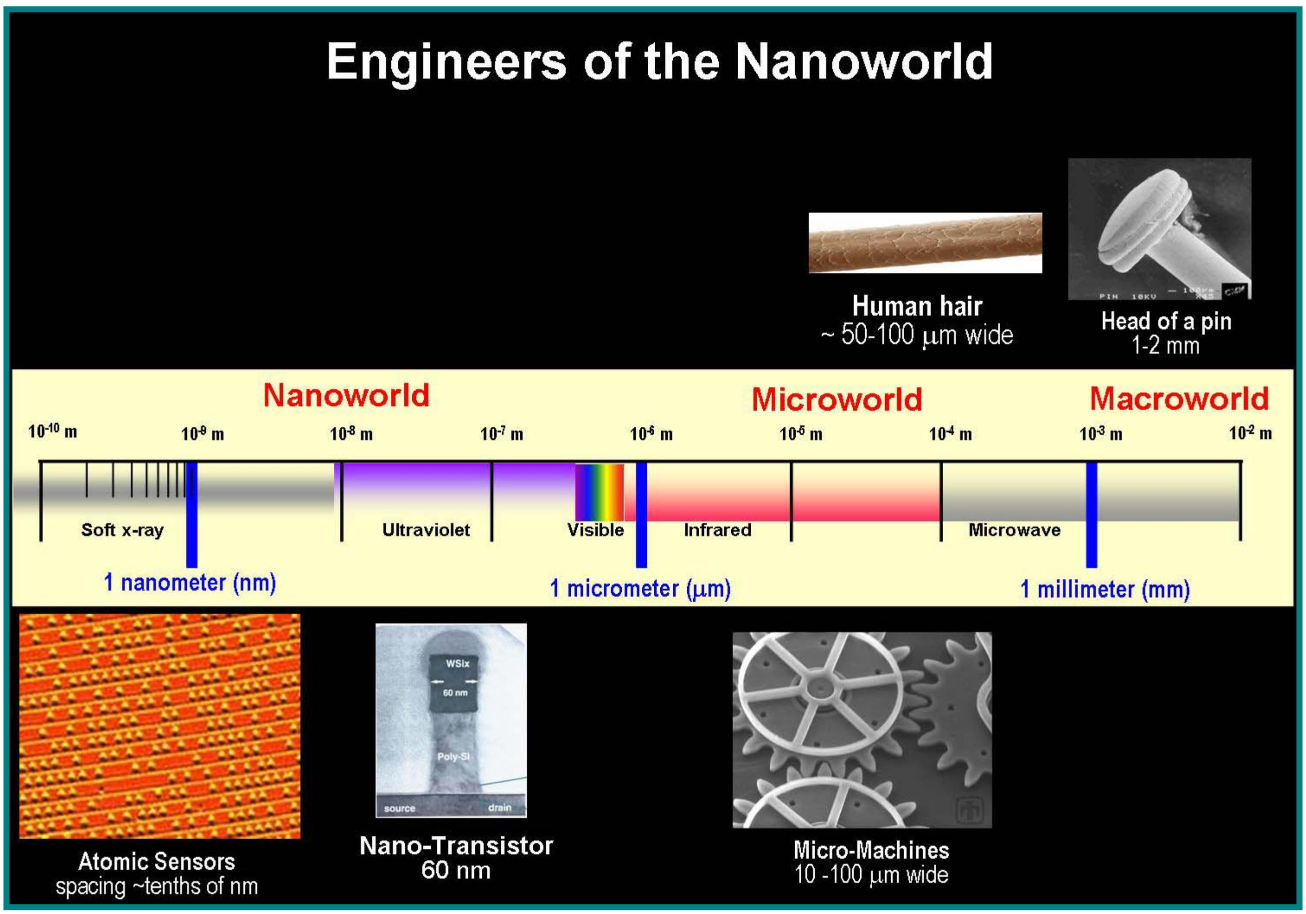
With the Defense Department's move to networked operations, precision time is becoming more critical. Today the warfighter relies on the time standard from GPS. However, when each communication node has a Chip Scale Atomic Clock they will no longer depend on GPS. With a Chip Scale Atomic Clock in each radio, the warfighter will never be alone or lost, even if the GPS signal is denied.

Another example of building a platform on a chip is a chip-scale hyperspectral imager.

In the laboratory, we know how to use hyperspectral techniques to precisely determine the wavelength composition of the photon radiation, and we can use this spectral information for target discrimination. But it is not practical to take a 10 cubic foot piece of hyperspectral imaging laboratory equipment out in the field.

Two years ago, John Carrano came up with an idea to develop infrared imagers where each pixel has a tunable wavelength response. No longer do we need to design an imager for a fixed wavelength response, never to be adjusted in the field.

By developing tunable MEMS resonant cavities at each pixel of an array, an adaptive focal plane array was conceived and is now showing early results. By applying a variable voltage at each pixel, the wavelength response can be tuned between different wavelengths at the chip-scale.



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We are now developing the algorithms for target discrimination and identification, along with the control electronics, to realize the full hyperspectral imager on a chip.

We are also working on other platforms on a chip, such as chip-scale micro gas analyzers, chip-scale atomic sensors, micro power generation, and intelligent RF front ends, to name just a few.

As we drive to open new performance and functional capabilities, we are also on the lookout for the revolutionary ideas that increase the performance in each of the five technical domains.

Today we are investing in new semiconductor materials that will enable unparalleled performance in photon sources such as light emitting diodes and lasers, power electronics, and microwave amplifiers. Wide bandgap semiconductors, namely silicon carbide and gallium nitride, are emerging from the laboratory to enable new device concepts.

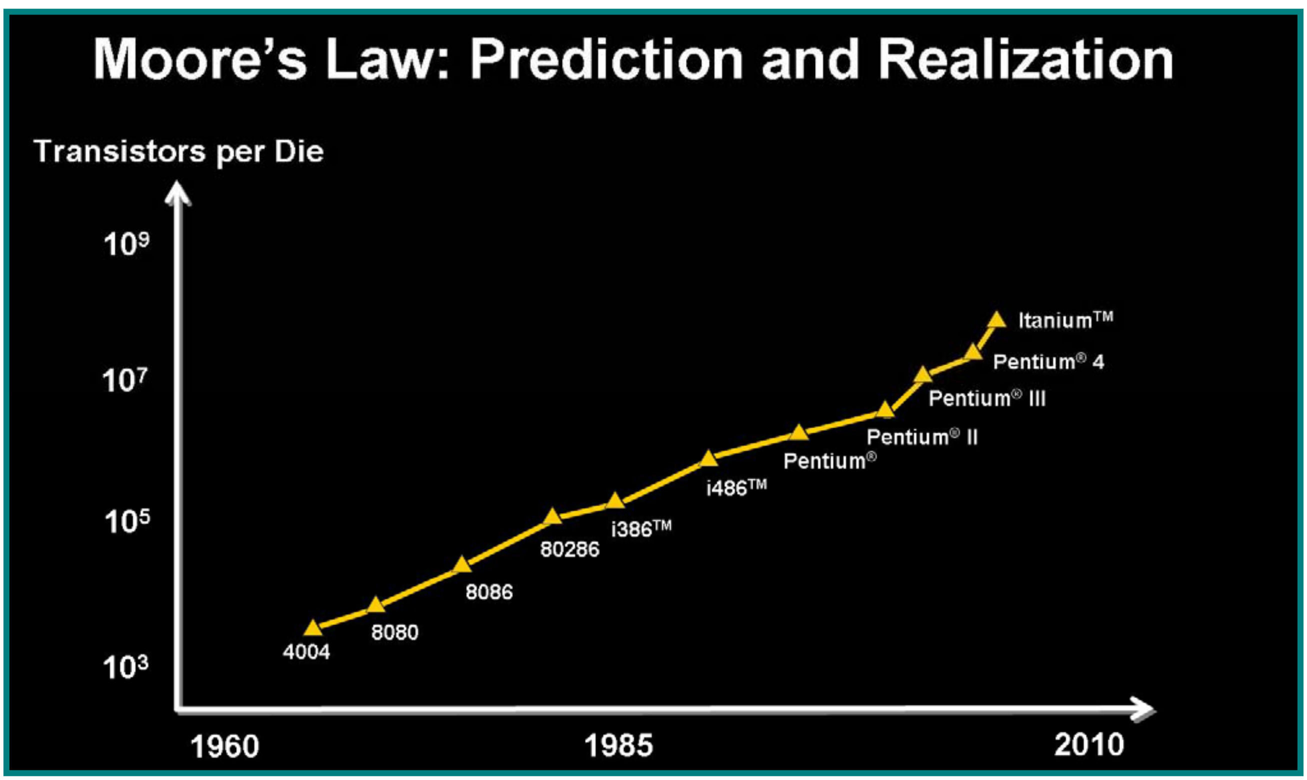
For example, gallium nitride light emitting diodes are now present in green traffic lights, and blue lasers are emerging in optical storage media. We are working to push this technology into the ultraviolet wavelengths, to alert Soldiers to biological threats, give them the ability to communicate covertly, and for use in water purification.

We are also exploiting the high voltage and high frequency capability of gallium nitride to develop the next generation of microwave amplifiers for radar, communications, and electronic warfare.

Three teams are under contract to move this new class of circuits from the laboratory into an industrial capability. When incorporated in the next generation of radars, these materials make it possible to get 10 times more power out of an RF transistor. This will allow the radar system users to track targets 80 percent farther away than with today's radar systems.

Technology Challenges

I told you about the five frontiers MTO is pushing to create platforms on a chip. But now I want to tell you about some of the cross-cutting technical challenges that are pacing our progress and that you can help us overcome.



Let me identify five:

1. Static Component Performance

Conventional component technology is fixed in performance after manufacturing. There is no ability to adjust the performance dynamically at the chip-scale. This limits system performance to predetermined operating conditions and limits our ability to respond to rapidly changing threats in the battle space.

2. Complexity in Component Design and Manufacturing

With progress in device scaling and integration, we are facing challenges in how we design microsystems with millions, or even billions of components.

Today's leading-edge integrated circuits have over 100 million transistors. We cannot do complete design verification and testing on such a complex system. On top of this, we are driving photonic integration onto this same chip-scale platform.

Adding new component functionality to simplify the overall microsystem design is one approach we are pursuing to mitigate complexity challenges. MTO Program Manager Jag Shah has a vision for combining Moore's Law for electronics with one for photonics.

3. Microsystem Optimization at the Nano-Scale

As we move device optimization further into the nano-scale, we must include the nano-physics of these structures in the optimization process.

Historically, we designed circuits with fixed device and interconnect models. Today's nano-scale devices have statistical variation in performance that must be handled in the optimized design. Can we develop a new design strategy based on statistical variation? Dennis Healy, our mathematician who also knows Microsystems technology, will tell you later how he is addressing this challenge with new design and optimization algorithms.

4. Integration of Disparate Materials

To realize the full potential of integrated microsystems, we need to bring different materials into functional contact.

We may need silicon for electronics, indium phosphide for lasers, diamond for heat spreading, and copper for interconnects. What are the processes for this? How do we overcome the material incompatibilities of thermal expansion, processing, and interdiffusion? What are the design rules here? What are the process tools?

5. Embedded Control and Sensing

The ultimate integrated microsystem must be able to sense its environment and adapt its performance to maximize information to the user.

How do we achieve this high level of control without driving the power requirements to extreme values? What are the new control algorithms? What is the processing model? What are the microsystems architectures? Steve Pappert has a vision of exploiting new photonic technology to address these questions.

Future Directions

I have mentioned some key technical challenges facing the engineers of the nano-world. In fact, every new program we are developing addresses these challenges to some degree.

Now, let me tell you about how I see the future of integrated microsystems. The future lies in reconfigurable and adaptable microsystems.

I want to build integrated microsystems whose performance can be reconfigured at the chip-scale. This is the idea of building in the capability to add a jumper wire or retune circuits at the chip-level. Reconfigurable components are ones whose performance can be modified at the chip-level to predetermined operating points after manufacturing.

I challenge you to think about how this change would impact decisions farther up the system food chain.

But let's not stop at reconfigurable microsystems that require external intervention to adjust their performance. The next step is to develop adaptable Microsystems.

For this we need to add the capability for the integrated microsystem to sense its environment and operating conditions, and then make autonomous decisions on how to reset its performance.

Suppose we are operating a radio frequency sensor in an environment with many competing signals and we want to detect a weak signal in the presence of large interfering signals. An adaptable receiver would be able to scan the frequency range and vary its bandwidth, sensitivity, and dynamic range automatically to zoom in on the signal of interest. Today we do this with predefined search routines that are constrained by the static hardware performance. An adaptable receiver would self-optimize for each scenario to more effectively find the desired signal.

If we can do this, we can quickly extend this concept to other scenarios, where there are changes in the environment, available power, or sensor Imagine how adaptable microsystems could be exploited.

While we see reconfigurable and adaptable microsystems as key focus areas for MTO going forward, our ultimate vision is to develop Intelligent microsytems—microsystems able to reason and learn with time. Microsystems that perform better the second time it encounters a scenario than the first time.

While this may be an impossible dream today, don't be surprised when, at some future DARPATech, the Director of the "Intelligent Integrated Microsystems Office" stands up here to explain how reconfigurable and adaptable microsystems are things of the past!

After all, I did start by asking you to believe five impossible things. OK, so maybe intelligent microsystems is the sixth.

Dr. Tether says that if you really want to work with DARPA the people to know are the program managers, especially the ones who are still formulating projects. I believe MTO has the best program managers in DARPA because they are make impossible dreams a reality. So get ready to view the future of integrated microsystems, where we are creating platforms on a chip that will be the foundation for future DoD capabilities.

Dream impossible dreams and join MTO to make them a reality.